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Title: Alkylidene complexes of ruthenium with N-
heterocyclic carbene ligands and their use as highly
active, selective catalysts for olefin metathesis

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Description

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Alkylidene complexes of ruthenium with N-heterocyclic carbene ligands and their use as highly active, selective catalysts for olefin metathesis

- 10 The invention relates to alkylidene complex compounds of ruthenium with N-heterocyclic carbene ligands and to a process for the preparation of olefins by olefin metathesis from acyclic olefins having two or more carbon atoms or/and from cyclic olefins having four or more carbon atoms,
15 wherein at least one of those alkylidene complex compounds is used as catalyst.

Transition-metal-catalyzed C-C linkages belong to the most important reactions of organic synthesis chemistry. Olefin
20 metathesis constitutes an important element in this connection, because it is possible by means of that reaction to synthesize olefins that are free of by-products. Olefin metathesis has high potential not only in the field of preparative organic synthesis (RCM,
25 ethenolysis, metathesis of acyclic olefins), but also in polymer chemistry (ROMP, ADMET, alkyne polymerization). Since its discovery in the 1950s, it has been possible to implement several large-scale processes. Nevertheless, olefin metathesis has only recently advanced to a widely
30 applicable synthesis method owing to the discovery of new catalysts (J.C. Mol in: B. Cornils, W.A. Herrmann: Applied Homogeneous Catalysis with Organometallic Compounds, VCH, Weinheim, 1996, p. 318-332; M. Schuster, S. Blechert, Angew. Chem. 1997, 109, 2124-2144; Angew. Chem. Int. Ed.
35 Engl. 1997, 36, 2036-2056).

Numerous standard works have made a substantial contribution towards the understanding of such transition-

metal-catalyzed reactions, in which an exchange of alkylidene units between olefins takes place. The generally accepted mechanism contains metal alkylidene complexes as the active species. These react with olefins to form metallacyclobutane intermediates, which generate olefins and alkylidene complexes again by cycloreversion. The isolation of metathesis-active alkylidene and metallacyclobutane complexes substantiates these mechanistic ideas.

Many examples are found primarily in the complex chemistry of molybdenum and tungsten. Schrock's works in particular have yielded well-defined alkylidene complexes which are controllable in terms of their reactivity (J.S. Murdzek, R.R. Schrock, *Organometallics* 1987, 6, 1373-1374). The introduction of a chiral ligand sphere into such complexes enabled the synthesis of polymers having high tacticity (K.M. Totland, T.J. Boyd, G.C. Lavoie, W.M. Davis, R.R. Schrock, *Macromolecules* 1996, 29, 6114-6125). Chiral complexes of the same structural type have also been used successfully in ring-closing metathesis (O. Fujimura, F.J.d.I. Mata, R.H. Grubbs, *Organometallics* 1996, 15, 1865-1871). However, high sensitivity towards functional groups, air and water is found to be a disadvantage.

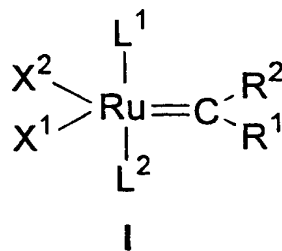
Phosphane-containing complex systems of ruthenium have recently become established (R.H. Grubbs, S.T. Nguyen, L.K. Johnson, M.A. Hillmyer, G.C. Fu, WO 96/04289, 1994; P. Schwab, M.B. France, J.W. Ziller, R.H. Grubbs, *Angew. Chem.* 1995, 107, 2179-2181; *Angew. Chem. Int. Ed. Engl.* 1995, 34, 2039-2041). Owing to the electron-rich, "soft" nature of later transition metals, such complexes have high tolerance towards hard, functional groups. This is demonstrated, for example, by their use in the chemistry of natural substances (RCM of dienes) (Z. Yang, Y. He, D. Vourloumis, H. Vallberg, K.C. Nicolaou, *Angew. Chem.* 1997, 109, 170-172; *Angew. Chem., Int. Ed. Engl.* 1997, 36, 166-168; D. Meng, P. Bertinato, A. Balog, D.S. Su, T. Kamenecka, E.J.

Sorensen, S.J. Danishefsky, J. Am. Chem. Soc. 1997, 119, 2733-2734; D. Schinzer, A. Limberg, A. Bauer, O.M. Böhm, M. Cordes, Angew. Chem. 1997, 109, 543-544; Angew. Chem., Int. Ed. Engl. 1997, 36, 523-524; A. Fürstner, K. Langemann, J. Am. Chem. Soc. 1997, 119, 9130-9136).

However, the range of variation of the phosphane ligands used is very limited on account of steric and electronic factors. Only strongly basic, sterically demanding alkylphosphanes such as tricyclohexyl-, triisopropyl- and tricyclopentyl-phosphane are suitable for the metathesis of acyclic olefins and slightly strained ring systems. Accordingly, such catalysts cannot be adjusted in terms of their reactivity. Nor has it been possible to produce chiral complexes of that structural type.

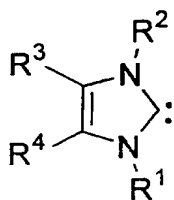
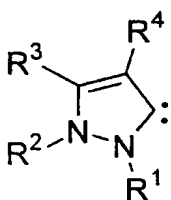
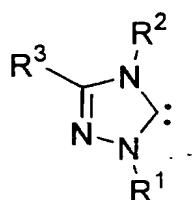
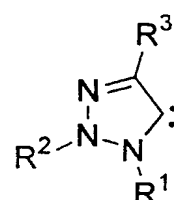
For those reasons, the object was to develop tailored metathesis catalysts which are distinguished by a variable ligand sphere as well as by high tolerance towards functional groups, and which allow fine adjustment of the catalyst for specific properties of different olefins. A further object was to provide a process for the preparation of olefins, in which process the reactivity is adjustable and chiral complexes can be produced.

The object is achieved according to the invention by a complex compound of ruthenium of the general structural formula I



in which X^1 and X^2 , which may be identical or different, represent an anionic ligand,

in which R^1 and R^2 are identical or different, but may also have a ring,
 in which R^1 and R^2 represent hydrogen or/and a hydrocarbon group, wherein the hydrocarbon groups, which may be
 5 identical or different, consist of straight-chain, branched, cyclic or/and non-cyclic radicals from the group alkyl radicals having from 1 to 50 carbon atoms, alkenyl radicals having from 1 to 50 carbon atoms, alkynyl radicals having from 1 to 50 carbon atoms, aryl radicals having from
 10 1 to 30 carbon atoms and silyl radicals, wherein the hydrogen atoms in the hydrocarbon or/and silyl groups may be replaced partially or wholly by one or more identical or different groups alkyl, aryl, alkenyl, alkynyl, metallocenyl, halogen, nitro, nitroso, hydroxy,
 15 alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio or/and sulfonyl,
 in which the ligand L^1 is a N-heterocyclic carbene of the general formulae **II** - **V** and in which the ligand L^2 is a neutral electron donor, especially a N-heterocyclic carbene
 20 of the general formulae **II** - **V** or an amine, imine, phosphane, phosphite, stibine, arsine, carbonyl compound, carboxyl compound, nitrile, alcohol, ether, thiol or thioether,

**II****III****IV****V**

25 wherein R^1 , R^2 , R^3 and R^4 in formulae **II**, **III**, **IV** and **V** may be identical or different and represent hydrogen or/and hydrocarbon groups,
 wherein the hydrocarbon groups consist of identical or different, cyclic, non-cyclic, straight-chain or/and

branched radicals from the group alkyl radicals having from 1 to 50 carbon atoms, alkenyl radicals having from 1 to 50 carbon atoms, alkynyl radicals having from 1 to 50 carbon atoms and aryl radicals having from 1 to 30 carbon atoms, in which at least one hydrogen may optionally be replaced by functional groups, and wherein R^3 and R^4 may optionally represent one or more identical or different groups halogen, nitro, nitroso, alkoxy, aryloxy, amido, carboxyl, carbonyl, thio or/and sulfonyl.

10

The complex compounds according to the invention are highly active catalysts for olefin metathesis. They are particularly inexpensive. Olefin metathesis using the catalysts according to the invention is distinguished by their great variety in the ligand sphere as well as by high tolerance towards very different functional groups. By varying the N-heterocyclic carbene ligands, which are readily accessible in terms of preparation, the activity and selectivity can be controlled in a targeted manner and, moreover, chirality can be introduced in a simple manner.

20

The anionic ligands X^1 and X^2 of the complex compound according to the invention may be identical or different and are preferably halide, pseudohalide, tetraphenyl borate, perhalogenated tetraphenyl borate, tetrahaloborate, hexahalophosphate, hexahaloantimonate, trihalomethanesulfonate, alkoxide, carboxylate, tetrahaloaluminate, tetracarbonyl cobaltate, hexahaloferate(III), tetrahaloferate(III) or/and tetrahalopalladate(II), wherein halide, pseudohalide, tetraphenyl borate, perfluorinated tetraphenyl borate, tetrafluoroborate, hexafluorophosphate, hexafluoroantimonate, trifluoromethanesulfonate, alkoxide, carboxylate, tetrachloroaluminate, tetracarbonyl cobaltate, hexafluoroferrate(III), tetrachloroferrate(III) or/and tetrachloropalladate(II) are preferred and wherein, of the pseudohalides, preference is given to cyanide, rhodanide, cyanate, isocyanate, thiocyanate and isothiocyanate.

30

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In the general formulae **II**, **III**, **IV** and **V**, the hydrogen in the hydrocarbon groups R^1 , R^2 , R^3 and R^4 may be replaced partially or wholly by one or more identical or different groups halogen, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio, sulfonyl or/and metallocenyl. In those formulae, R^3 and R^4 may represent a fused ring system.

- 10 The ligands L^1 and L^2 of the complex compound of the general structural formula **I** may form a chelate ligand of the general formula **VI**



VI

- wherein the bridging members designated **Y** may consist of cyclic, non-cyclic, straight-chain or/and branched radicals from the group alkylene radicals having from 1 to 50 carbon atoms, alkenylene radicals having from 1 to 50 carbon atoms, alkynylene radicals having from 1 to 50 carbon atoms, arylene radicals having from 1 to 30 carbon atoms, metallocenylene, borylene and silylene radicals, in which at least one hydrogen may optionally be substituted by one or more identical or different groups alkyl, aryl, alkenyl, alkynyl, metallocenyl, halogen, nitro, nitroso, hydroxo, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio or/and sulfonyl, preferably by alkyl, aryl or/and metallocenyl.

- The alkyl radicals, alkenyl radicals, alkynyl radicals, or the alkylene radicals, alkenylene radicals, alkynylene radicals, in formulae **I** to **VII** preferably have from 1 to 20 carbon atoms, particularly preferably from 1 to 12 carbon atoms.

The ligands of the general formulae **II**, **III**, **IV**, **V** or/and **VI** may have central, axial or/and planar chirality.

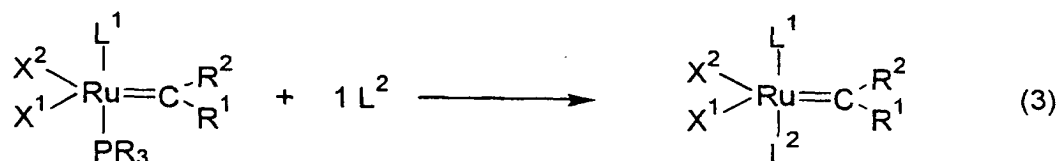
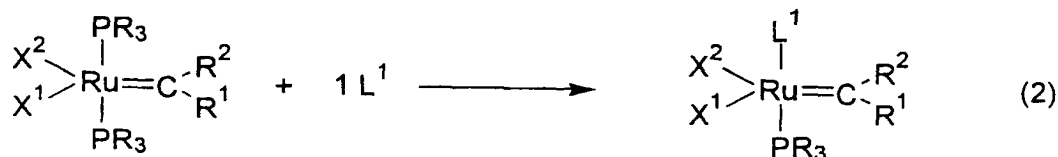
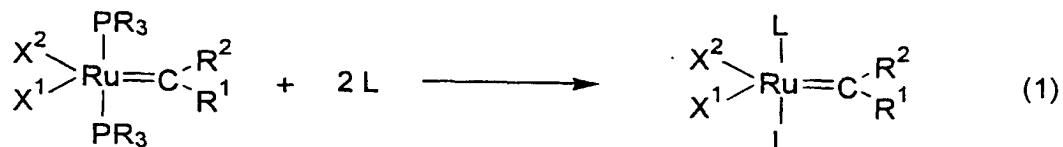
In the general structural formula **I** of the complex
5 compound, R^1 to R^2 preferably represent hydrogen,
substituted or/and unsubstituted alkyl, alkenyl or/and aryl
radicals, X^1 and X^2 are preferably halide, alkoxide or/and
carboxylate ions, and L^1 and L^2 preferably represent a N-
heterocyclic carbene of the general formula **II**.

10

The synthesis of the complexes is usually carried out by
ligand substitution of appropriate phosphane complexes.
Those complexes may be selectively disubstituted according
to reaction equation (1) or monosubstituted according to
15 reaction equation (2). In the case of monosubstitution, the
second phosphane may be selectively substituted by a
different electron donor, e.g. pyridine, phosphane, N-
heterocycle carbene, phosphite, stibine, arsine, according
to reaction equation (3).

20

In that manner it is possible in particular to prepare for
the first time chiral ruthenium-based catalysts having
metathesis activity (complex examples **2** and **3**).



The complex compounds according to the invention prove to be extremely efficient catalysts in olefin metathesis. The excellent metathesis activity is demonstrated in the

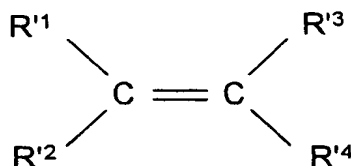
5 Examples by means of several examples of different metathesis reactions.

Accordingly, this invention also includes the processes of all olefin metathesis reactions, such as ring-opening
 10 metathesis polymerization (ROMP), metathesis of acyclic olefins, ethenolysis, ring-closing metathesis (RCM), acyclic diene metathesis polymerization (ADMET) and depolymerization of olefinic polymers. The high stability and tolerance of the complex compounds according to the
 15 invention towards functional groups, especially groups of alcohols, amines, thiols, ketones, aldehydes, carboxylic acids, esters, amides, ethers, silanes, sulfides and halogens, permits the presence of such functional groups during the metathesis reaction.

20

The object is further achieved by a process for the preparation of acyclic olefins having two or more carbon

atoms or/and of cyclic olefins having four or more carbon atoms, in each case corresponding to the general formula **VII**



VII

- 5 from acyclic olefins having two or more carbon atoms or/and from cyclic olefins having four or more carbon atoms, in each case corresponding to the general formula **VII**, by olefin metathesis reaction in the presence of at least one catalyst, wherein a catalyst as claimed in any one of
- 10 claims 1 to 7 is used and R'¹, R'², R'³ and R'⁴ in the general formula **VII** represent hydrogen or/and hydrocarbon groups, wherein the hydrocarbon group consists of identical or different straight-chain, branched, cyclic or/and non-cyclic radicals from the group alkyl radicals having from 1
- 15 to 50 carbon atoms, alkenyl radicals having from 1 to 50 carbon atoms, alkynyl radicals having from 1 to 50 carbon atoms, aryl radicals having from 1 to 30 carbon atoms, metallocenyl or/and silyl radicals, in which at least one hydrogen may optionally be replaced by a functional group,
- 20 wherein R'¹, R'², R'³ and R'⁴ optionally represent one or more identical or different groups halogen, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio, sulfonyl or/and metallocenyl.
- 25 The olefins that are used or/and that are to be prepared preferably contain one or/and more than one double bond. One or more of R'¹, R'², R'³ and R'⁴, identical or different, in the olefins of the general formula **VII**, in pairs, especially form a ring. The hydrogen in the hydrocarbon
- 30 groups R'¹, R'², R'³ and R'⁴ in the olefins of the general

formula **VII** has preferably been replaced partially or wholly by one or more identical or different groups halogen, silyl, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio, sulfonyl or/and
5 metallocenyl.

In the process according to the invention, the process may be carried out with or without a solvent, but preferably with organic solvents. The process according to the
10 invention can preferably be carried out with the addition of a Brönstedt acid, preferably HCl, HBr, HI, HBF₄, HPF₆ or/and trifluoroacetic acid, or/and with the addition of a Lewis acid, preferably BF₃, AlCl₃ or/and ZnI₂.

15 Surprisingly, it accordingly becomes possible for the first time to tailor the most varied olefins individually to different properties on the basis of a slight variation in the catalysis conditions or/and in the catalysts, because the process according to the invention for the preparation
20 of olefins has unexpectedly high tolerance towards functional groups.

Examples:

25 The Examples which follow illustrate the invention but do not limit the scope thereof.

1) Preparation of the complex compound according to the invention

30

General working procedure:

1 mmol. of (PPh₃)₂Cl₂Ru(=CHPh) was dissolved in 20 ml of toluene, and a solution of 2.2 equiv. of the appropriate
35 imidazolin-2-ylidene in 5 ml of toluene was added thereto. The reaction solution was stirred for 45 minutes at room temperature RT and then concentrated to about 2 ml, and the

crude product was precipitated with 25 ml of pentane. The crude product was taken up several times in 2 ml of toluene and precipitated with 25 ml of pentane. The residue was extracted with toluene, and the solution was concentrated to dryness, washed twice with pentane and dried for several hours under a high vacuum.

For characterization purposes, the data of low-temperature NMR spectra are for the most part given, because some of the spectra at room temperature do not contain all the information on account of dynamic effects.

The following compounds are prepared according to the indicated general working procedure:

15

1a) Benzylidene-dichloro-bis(1,3-diisopropylimidazolin-2-ylidene)-ruthenium - complex compound 1:

Yield: 487 mg (0.86 mmol. = 86 % of theory)

20 Elemental analysis **EA** for $C_{25}H_{38}Cl_2N_4Ru$ (566.58):

found C 53.21 H 6.83 N 9.94;

calculated C 53.00 H 6.76 N 9.89.

1H -NMR ($CD_2Cl_2/200$ K): δ 20.33 (1H, s, Ru=CH), 8.25 (2H, d, $^3J_{HH} = 7.6$ Hz, o-H of C_6H_5), 7.63 (1H, t, $^3J_{HH} = 7.6$ Hz, p-H of C_6H_5), 7.34 (2H, t, m-H of C_6H_5 , $^3J_{HH} = 7.6$ Hz), 7.15 (2H, br, NCH), 7.03 (2H, br, NCH), 5.97 (2H, spt, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 3.73 (2H, spt, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 1.64 (12H, d, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 1.11 (6H, d, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 0.75 (6H, d, $^3J_{HH} = 6.4$ Hz, NCHMe₂).

30 **^{13}C -NMR** ($CD_2Cl_2/200$ K): δ 295.6 (Ru=CH), 183.5 (NCN), 151.6 (ipso-C of C_6H_5), 129.5, 128.6 and 128.1 (o-C, m-C and p-C of C_6H_5), 118.1 and 117.2 (NCH), 52.1 and 50.1 (NCHMe₂), 24.5, 23.8, 23.8 and 22.4 (NCHMe₂).

1b) Benzylidene-dichloro-bis(1,3-di-((R)-1'-phenylethyl)-imidazolin-2-ylidene)-ruthenium - complex compound 2:

Yield: 676 mg (0.83 mmol. = 83 % of theory)

5 **EA** for $C_{45}H_{46}Cl_2N_4Ru$ (814.86): found C 66.48 H 5.90 N 6.73;
calc. C 66.33 H 5.69 N 6.88

1H -NMR ($CD_2Cl_2/200$ K): δ 20.26 (1H, s, Ru=CH), 8.13 (2H, br, o-H C_6H_5), 7.78-6.67 (29H, of which 2*m*-H and 1*p*-H of C_6H_5 , 20H of NCHMePh, 2H of NCHMePh and 4H of NCH), 4.91 (2H, m, NCHMePh), 1.84 (3H, d, $^3J_{HH} = 6.6$ Hz, NCHMePh), 1.81 (3H, d, $^3J_{HH} = 6.6$ Hz, NCHMePh), 1.51 (3H, d, $^3J_{HH} = 6.6$ Hz, NCHMePh), 1.21 (3H, d, $^3J_{HH} = 6.6$ Hz, NCHMePh).

10 **^{13}C -NMR** ($CD_2Cl_2/200$ K): δ 294.7 (Ru=CH), 186.0 and 185.6 (NCN), 151.2 (*ipso*-C of C_6H_5), 141.2, 140.3, 140.1 and 139.9 (15 *ipso*-C of NCHMePh), 133.1-125.9 (o-C, *m*-C, *p*-C of C_6H_5 and NCHMePh), 120.5, 119.9, 119.2 and 118.8 (NCH), 57.6, 57.4, 56.7 and 56.1 (NCHMePh), 22.2, 20.6, 20.4 and 20.3 (NCHMePh).

20 **1c) Benzylidene-dichloro-bis(1,3-di((R)-1'-naphthylethyl)-imidazolin-2-ylidene)-ruthenium - complex compound 3:**

Yield: 792 mg (0.78 mmol. = 78 % of theory)

EA for $C_{61}H_{54}Cl_2N_4Ru$ (1015.1): found C 72.34 H 5.46 N 5.45;
25 calc. C 72.18 H 5.36 N 5.52.

1H -NMR ($CD_2Cl_2/260$ K): δ 20.90 (1H, s, Ru=CH), 8.99 (2H, br, o-H of C_6H_5), 8.2-5.6 (39H, of which 2*m*-H and 1*p*-H of C_6H_5 , 28H of NCHMeNaph, 4H of NCH and 4H of NCHMeNaph), 2.5-0.8 (12H, m, NCHMeNaph).

30 **^{13}C -NMR** ($CD_2Cl_2/260$ K): δ 299.9 (Ru=CH), 187.2 and 184.7 (NCN), 152.0 (*ipso*-C of C_6H_5), 136.0-124.0 (o-C, *m*-C, *p*-C of C_6H_5 and NCHMeNaph), 121.7, 121.0, 119.9 and 118.9 (NCH), 56.7, 56.1, 55.0 and 54.7 (NCHMeNaph), 24.7, 24.3, 21.0 and 20.0 (NCHMeNaph).

35

Slight deviations from the general working procedure are necessary for the following complexes:

1d) (4-Chlorobenzylidene)-dichloro-bis(1,3-diisopropyl-imidazolin-2-ylidene)-ruthenium - complex compound 4:

5 1 mmol. of $(PPh_3)_2Cl_2Ru[=CH(p-C_6H_4Cl)]$ was used as starting material. The further procedure corresponded to the general working procedure.

Yield: 535 mg (0.89 mmol. = 89 % of theory)

EA for $C_{24}H_{38}Cl_3N_4Ru$ (601.03): found C 48.13 H 6.33 N 9.24;

10 calc. C 47.96 H 6.37 N 9.32.

1H -NMR ($CD_2Cl_2/200$ K): δ 20.33 (1H, s, Ru=CH), 8.25 (2H, d, $^3J_{HH} = 7.6$ Hz, o-H of C_6H_4Cl), 7.63 (1H, t, $^3J_{HH} = 7.6$ Hz, m-H of C_6H_4Cl), 7.15 (2H, br, NCH), 7.03 (2H, br, NCH), 5.97 (2H, spt, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 3.73 (2H, spt, $^3J_{HH} =$
15 6.4 Hz, NCHMe₂), 1.64 (12H, d, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 1.11 (6H, d, $^3J_{HH} = 6.4$ Hz, NCHMe₂), 0.75 (6H, d, $^3J_{HH} = 6.4$ Hz, NCHMe₂).

^{13}C -NMR ($CD_2Cl_2/200$ K): δ 295.6 (Ru=CH), 183.5 (NCN), 151.6 (ipso-C of C_6H_4Cl), 134.3 (p-C of C_6H_4Cl), 128.6 and 128.1
20 (o-C and m-C of C_6H_4Cl), 118.1 and 117.2 (NCH), 52.1 and 50.1 (NCHMe₂), 24.5, 23.8, 23.8 and 22.4 (NCHMe₂).

1e) Benzylidene-dichloro-bis(1,3-dicyclohexylimidazolin-2-ylidene)-ruthenium - complex compound 5:

25

1 mmol. of $(PPh_3)_2Cl_2Ru(=CHPh)$ was dissolved in 25 ml of toluene, and a solution of 2.2 equiv. of 1,3-dicyclohexylimidazolin-2-ylidene in 5 ml of toluene was added thereto. The reaction solution was stirred for 45 minutes at RT and
30 then freed of solvent. Unlike in the general working procedure, the crude product was purified by flash chromatography.

Yield: 305 mg (0.42 mmol. = 42 % of theory)

EA for $C_{37}H_{54}Cl_2N_4Ru$ (726.84): found C 61.23 H 7.56 N 7.87;

35 calc. C 61.14 H 7.49 N 7.71.

1H -NMR ($CD_2Cl_2/298$ K): δ 20.45 (1H, s, Ru=CH), 8.31 (2H, d, $^3J_{HH} = 7.6$ Hz, o-H- of C_6H_5), 7.63 (1H, t, $^3J_{HH} = 7.6$ Hz, p-H-

of C₆H₅), 7.34 (2H, t, ³J_{HH} = 7.6 Hz, *m*-H- of C₆H₅), 7.14 (2H, br, NCH), 7.00 (2H, br, NCH), 6.06 (2H, br, CH of NC₆H₁₁), 3.82 (2H, br, CH of NC₆H₁₁), 1.64 (12H, br, CH₂ of NC₆H₁₁), 0.93 (12H, br, CH₂ of NC₆H₁₁).

5 ¹³C-NMR (CD₂Cl₂/298 K): δ 299.4 (Ru=CH), 182.9 (NCN), 152.0 (*ipso*-C of C₆H₅), 131.1, 129.8 and 129.1 (*o*-C, *m*-C and *p*-C of C₆H₅), 118.3 and 117.8 (br, NCH), 59.6 and 57.5 (br, CH of NC₆H₁₁), 35.7, 26.9 and 25.6 (br, CH₂ of NC₆H₁₁).

10 **1f) Benzylidene-dichloro-(1,3-di-*tert*.-butylimidazolin-2-ylidene)-(triphenylphosphine)-ruthenium - complex compound 6:**

1 mmol. of (PPh₃)₂Cl₂Ru(=CHPh) was dissolved in 20 ml of
15 toluene, and a solution of 1.1 equiv. of 1,3-di-*tert*.-butylimidazolin-2-ylidene in 5 ml of toluene was added thereto. The reaction solution was stirred for 30 minutes at RT and then concentrated to about 2 ml, and the crude product was precipitated with 25 ml of pentane. Further
20 working-up was carried out in accordance with the general working procedure.

Yield: 493 mg (0.70 mmol. = 70 % of theory)

EA for C₃₆H₄₁Cl₂N₂P₁Ru (704.69):

found C 61.12 H 5.55 N 3.62 P 4.59
25 calc. C 61.36 H 5.86 N 3.98 P 4.38.

¹H-NMR (CD₂Cl₂/200 K): δ 20.70 (1H, s, Ru=CH), 8.03 (2H, d, ³J_{HH} = 7.6 Hz, *o*-H of C₆H₅), 7.50-6.95 (20H, of which 2*m*-H and 1*p*-H of C₆H₅, 15H of PPh₃ and 2H of NCH), 1.86 (9H, s, NCMe₃), 1.45 (9H, s, NCMe₃).

30 ¹³C-NMR (CD₂Cl₂/200 K): δ 307.4 (br, Ru=CH), 178.3 (d, J_{PC} = 86 Hz, NCN), 151.5 (d, J_{PC} = 4.5 Hz, *ipso*-C of C₆H₅), 135.0 (*m*, *o*-C of PPh₃), 131.9 (*m*, *ipso*-C of PPh₃), 130.2 (*s*, *p*-C of PPh₃), 129.5, 128.6 and 128.1 (*s*, *o*-C, *m*-C and *p*-C of C₆H₅), 128.0 (*m*, *m*-C of PPh₃), 117.7 and 117.6 (NCH), 58.7
35 and 58.5 (NCMe₃), 30.0 and 29.5 (NCMe₃).

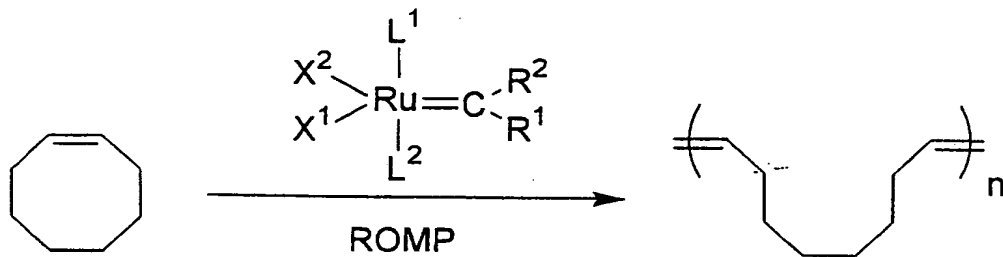
³¹P-NMR (CD₂Cl₂/200 K): δ 40.7 (*s*, PPh₃).

2) Use of the complex compound according to the invention in olefin metathesis

The Examples given hereinbelow demonstrate the potential of the complex compounds according to the invention in olefin metathesis. The advantage of the complex compounds according to the invention compared with phosphane-containing complexes is that the radicals R on the nitrogen atoms of the N-heterocyclic carbene ligands can be varied in a targeted and inexpensive manner. By tailoring the catalysts according to the invention in that manner relative to individual properties of the olefins to be metathesized, the activity and the selectivity of the reaction can be controlled.

2a) Ring-opening metathesis polymerization (ROMP):

Norbornene, cyclooctene and functionalized norbornene derivatives are used as examples.



(4)

Typical reaction batch for the polymerization of cyclooctene (or norbornene):

410 μ l (3.13 mmol.) of cyclooctene were introduced into a solution of 3.6 mg (6.3 μ mol.) of 1 in 0.5 ml of methylene chloride. After about 10 minutes, a highly viscous gel had formed, which could no longer be stirred. 1 ml of methylene chloride was added. This procedure was repeated whenever

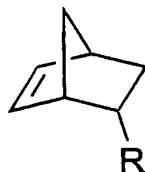
the stirrer ceased to perform (3 ml of methylene chloride in total). After 1 hour, 5 ml of methylene chloride were added, to which small amounts of tert.-butyl ether and 2,6-di-tert.-butyl-4-methylphenol had been added. After a further 10 minutes, the solution was slowly added dropwise to a large excess of methanol, and the whole was filtered and dried for several hours under a high vacuum.
Yield: 291 mg (2.64 mmol. = 84.3 % of theory)

Table 1. Polymerization of norbornene and cyclooctene

Example	Complex	Monomer	Ratio [monomer]/ [cat.]	Reaction time t	Yield
2.1a	<u>1</u>	norbornene	100:1	1 min	91 %
2.1b	<u>5</u>	norbornene	100:1	1 min	92 %
2.1c	<u>1</u>	cyclooctene	500:1	1 h	84 %
2.1d	<u>1</u>	cyclooctene	500:1	2 h	97 %
2.1e	<u>5</u>	cyclooctene	500:1	1 h	87 %

Typical reaction batch for the polymerization of functionalized norbornene derivatives:

Formula **VIII** illustrates the basic structure of the norbornene derivatives used in Table 2.



VIII

0.3 ml of a solution of 432 mg (3.13 mmol.) of 5-carboxylic acid 2-norbornene (formula **VIII** with R = CO₂H) in methylene

chloride was added to a solution of 3.6 mg (6.3 $\mu\text{mol.}$) of 1 in 0.2 ml of methylene chloride. After about 10 minutes, a highly viscous gel had formed, which could no longer be stirred. A further 0.5 ml of methylene chloride was added.

5 This procedure was repeated whenever the stirrer ceased to perform. After 1 hour, 5 ml of methylene chloride were added, to which small amounts of tert.-butyl ether and 2,6-di-tert.-butyl-4-methylphenol had been added. After a further 10 minutes, the solution was slowly added dropwise
10 to a large excess of methanol, and the whole was filtered and dried for several hours under a high vacuum.

Yield: 423 mg (3.06 mmol. = 98.1 % of theory)

The reactions at 50°C were carried out in an analogous manner in dichloroethane instead of methylene chloride.

15

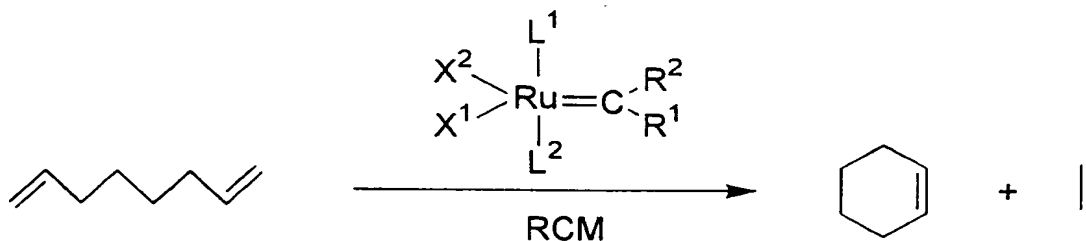
Table 2. Polymerization of functionalized norbornene derivatives

Example	Complex	Radical R in formula VIII	T [°C]	Reaction time t	Yield
2.1f	<u>1</u>	O ₂ CCH ₃	25	30 min	99 %
2.1g	<u>1</u>	CH ₂ OH	25	2 h	15 %
2.1h	<u>1</u>	CH ₂ OH	50	2 h	18 %
2.1i	<u>1</u>	CHO	25	2 h	36 %
2.1k	<u>1</u>	CHO	50	2 h	52 %
2.1l	<u>1</u>	COCH ₃	25	2 h	42 %
2.1m	<u>1</u>	COCH ₃	50	2 h	67 %
2.1n	<u>1</u>	CO ₂ H	25	2 h	98 %

20 The polymerization of norbornene took place within a period of seconds. In the cyclooctene polymerization, almost quantitative conversions were obtained within an hour (Table 1). Differences in respect of activity can be demonstrated by the use of different complexes under dilute
25 conditions and show the dependence of the activity on the

substitution pattern of the carbene ligands used. The high stability and tolerance towards functional groups is demonstrated by the polymerization of functionalized norbornene derivatives with esters, alcohol, aldehyde, ketone or/and carboxylic acid (Table 2). It has thereby been possible to polymerize monomers of the general formula **VIII** wherein R = CH₂OH, CHO and CO₂H for the first time.

2.2) Ring-closing metathesis (RCM) of 1,7-octadiene:



(5)

Typical reaction batch for the RCM of 1,7-octadiene:

46 μ l (0.31 mmol.) of 1,7-octadiene were added to a solution of 3.6 mg (6.3 μ mol.) of **1** in 2 ml of dichloroethane, and the reaction batch was placed in an oil bath at 60°C. After 1 hour, the reaction mixture was examined by GC/MS analysis.

Table 3. RCM of 1,7-octadiene (octadiene/catalyst = 50:1)

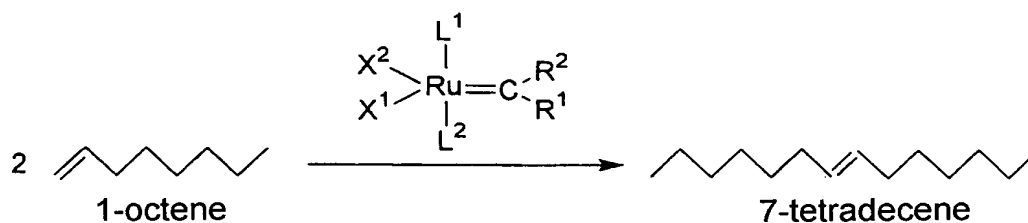
Example	Complex	Solvent	T [°C]	Reaction time t	Yield
2.2a	<u>1</u>	methylene chloride	25	5.5 h	51 %
2.2b	<u>1</u>	methylene chloride	25	24 h	70 %
2.2c	<u>1</u>	dichloroethane	60	1 h	99 %
2.2d	<u>2</u>	dichloroethane	60	1 h	99 %
2.2e	<u>3</u>	dichloroethane	60	1 h	99 %
2.2f	<u>5</u>	dichloroethane	60	1 h	99 %

The potential in the ring-closing metathesis has been
 5 illustrated by the reaction of 1,7-octadiene to cyclohexene
 with the liberation of ethylene (Table 3). With 1, a yield
 of 51 % was achieved after 5.5 hours; at 60°C, quantitative
 conversions were even achieved with all the complex
 compounds according to the invention which were used.

10

2.3) Metathesis of acyclic olefins

A) Metathesis of 1-octene:



15

(6)

Typical reaction batch for the metathesis of 1-octene:
 49 μl (0.31 mmol.) of 1-octene were added to a solution of
 3.6 mg (6.3 $\mu\text{mol.}$) of 1 in 2 ml of dichloroethane, and the
 20 reaction batch was placed in an oil bath at 60°C. After

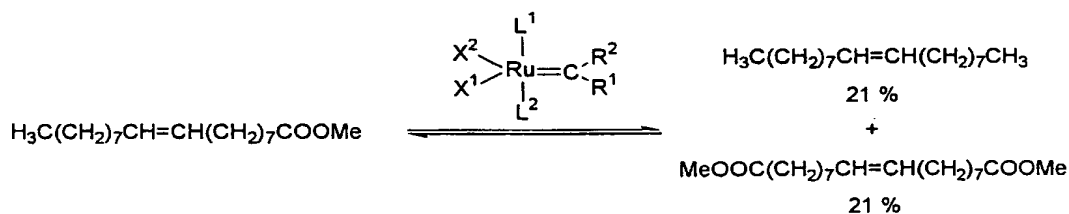
3 hours, the reaction mixture was examined by GC/MS analysis.

Table 4. Homo-metathesis of 1-octene (octene/catalyst = 50:1)

Example	Complex	T [°C]	Reaction time t	Conversion of 1-octene	Selectivity ^a
2.3a	<u>2</u>	60	1 h	31 %	98 %
2.3b	<u>2</u>	60	2 h	58 %	97 %
2.3c	<u>1</u>	60	1 h	83 %	73 %
2.3d	<u>1</u>	60	3 h	97 %	63 %

^a The selectivity indicates the proportion of 7-tetradecene compared with other metathesis products

B) Metathesis of methyl oleate:



(7)

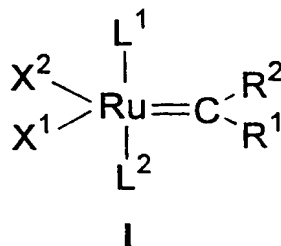
Typical reaction batch for the metathesis of methyl oleate:

1.06 ml (3.13 mmol.) of methyl oleate were added to a solution of 3.6 mg (6.3 μmol.) of 1 in 0.5 ml of dichloroethane, and the reaction batch was placed in an oil bath at 60°C for 15 hours. GC/MS analysis yielded the equilibrium of metathesis products shown in reaction equation (7).

The metathesis of terminal and internal olefins has been demonstrated by the homo-metathesis of 1-octene and methyl oleate. In the metathesis of methyl oleate as a natural raw material, the thermodynamic equilibrium can almost be
5 reached within a period of 15 hours with catalyst 1 at an olefin:catalyst ratio of 500:1. In the metathesis of 1-octene, 7-tetradecene was not obtained as the only reaction product in all cases. An isomerization, detected by NMR
10 spectroscopy, of 1-octene to 2-octene and subsequent olefin metathesis is responsible for that situation. Homo- and cross-metathesis of 1-octene and 2-octene yielded, in addition to 7-tetradecene, also 6-tridecene as the most frequent by-product, and small amounts of 6-dodecene, 1-heptene and 2-nonene. The product distribution is greatly
15 dependent on the catalyst used. In the case of 2, 7-tetradecene was obtained almost selectively; the more active complex 1, on the other hand, yielded 7-tetradecene with a selectivity of only 63 %, at a high conversion. 6-Tridecene was obtained as the principal by-product of the
20 cross-metathesis of 1-octene with 2-octene.

Patent claims:

1. A complex compound of ruthenium of the general structural formula **I**



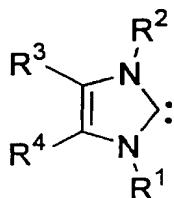
5

in which X^1 and X^2 , which may be identical or different, represent an anionic ligand,

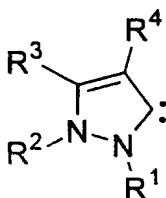
in which R^1 and R^2 are identical or different, but may also have a ring,

10 in which R^1 and R^2 represent hydrogen or/and a hydrocarbon group, wherein the hydrocarbon groups, which may be identical or different, consist of straight-chain, branched, cyclic or/and non-cyclic radicals from the group alkyl radicals having from 1 to 50 carbon atoms, alkenyl
15 radicals having from 1 to 50 carbon atoms, alkynyl radicals having from 1 to 50 carbon atoms, aryl radicals having from 1 to 30 carbon atoms and silyl radicals, wherein the hydrogen atoms in the hydrocarbon or/and silyl groups may be replaced partially or wholly by one or more
20 identical or different groups alkyl, aryl, alkenyl, alkynyl, metallocenyl, halogen, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio or/and sulfonyl,

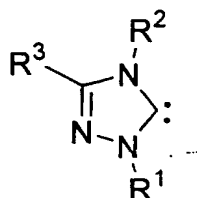
in which the ligand L^1 is a N-heterocyclic carbene of the
25 general formulae **II - V** and in which the ligand L^2 is a neutral electron donor, especially a N-heterocyclic carbene of the general formulae **II - V** or an amine, imine, phosphane, phosphite, stibine, arsine, carbonyl compound, carboxyl compound, nitrile, alcohol, ether, thiol or
30 thioether,



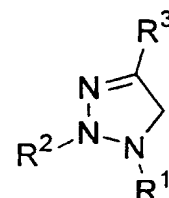
II



III



IV



V

wherein R^1 , R^2 , R^3 and R^4 in formulae **II**, **III**, **IV** and **V** may be identical or different and represent hydrogen or/and hydrocarbon groups,

- 5 wherein the hydrocarbon groups consist of identical or different, cyclic, non-cyclic, straight-chain or/and branched radicals from the group alkyl radicals having from 1 to 50 carbon atoms, alkenyl radicals having from 1 to 50 carbon atoms, alkynyl radicals having from 1 to 50 carbon atoms and aryl radicals having from 1 to 30 carbon atoms, in which at least one hydrogen may optionally be replaced by functional groups, and wherein R^3 and R^4 may optionally represent one or more identical or different groups halogen, nitro, nitroso, alkoxy, aryloxy, amido, carboxyl, carbonyl, thio or/and sulfonyl.

2. The complex compound as claimed in claim 1, wherein the anionic ligands X^1 and X^2 may be identical or different and are halide, pseudohalide, tetraphenyl borate, perhalogenated tetraphenyl borate, tetrahaloborate, hexahalophosphate, hexahaloantimonate, trihalomethanesulfonate, alkoxide, carboxylate, tetrahaloaluminate, tetracarbonyl cobaltate, hexahaloferate(III), tetrahaloferate(III) or/and tetrahalopalladate(II), wherein halide, pseudohalide, tetraphenyl borate, perfluorinated tetraphenyl borate, tetrafluoroborate, hexafluorophosphate, hexafluoroantimonate, trifluoromethanesulfonate, alkoxide, carboxylate, tetrachloroaluminate, tetracarbonyl cobaltate, hexafluoroferrate(III),

tetrachloroferrate(III) or/and tetrachloropalladate(II) are preferred and wherein, of the pseudohalides, preference is given to cyanide, rhodanide, cyanate, isocyanate, thiocyanate and isothiocyanate.

5

3. The complex compound as claimed in claim 1 and 2, wherein in the general formulae **II**, **III**, **IV** and **V**, the hydrogen in the hydrocarbon groups R^1 , R^2 , R^3 and R^4 has been replaced partially or wholly by one or more identical or
 10 different groups halogen, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio, sulfonyl or/and metallocenyl.

4. The complex compound as claimed in any one of claims 1
 15 to 3, wherein R^3 and R^4 in the general formulae **II**, **III**, **IV** and **V** represent a fused ring system.

5. The complex compound as claimed in any one of claims 1 to 4, wherein L^1 and L^2 form a chelate ligand of the general
 20 formula **VI**



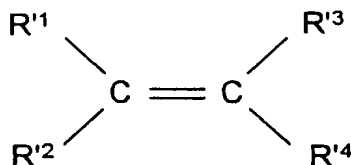
VI

wherein the bridging members designated **Y** consist of cyclic, non-cyclic, straight-chain or/and branched radicals from the group alkylene radicals having from 1 to 50 carbon
 25 atoms, alkenylene radicals having from 1 to 50 carbon atoms, alkynylene radicals having from 1 to 50 carbon atoms, arylene radicals having from 1 to 30 carbon atoms, metallocenylene, borylene and silylene radicals, in which at least one hydrogen may optionally be substituted by one
 30 or more identical or different groups alkyl, aryl, alkenyl, alkynyl, metallocenyl, halogen, nitro, nitroso, hydroxo, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio or/and sulfonyl.

6. The complex compound as claimed in any one of claims 1 to 5, wherein the ligands of the general formulae **II**, **III**, **IV**, **V** or/and **VI** have central, axial or/and planar
5 chirality.

7. The complex compound as claimed in any one of claims 1 to 6, wherein in the general structural formula **I**, R^1 to R^2 represent hydrogen, substituted or/and unsubstituted alkyl,
10 alkenyl or/and aryl radicals, X^1 and X^2 are halide, alkoxide or/and carboxylate ions, or/and L^1 and L^2 represent a N-heterocyclic carbene of the general formula **II**.

8. A process for the preparation of acyclic olefins
15 having two or more carbon atoms or/and of cyclic olefins having four or more carbon atoms, in each case corresponding to the general formula **VII**



VII

from acyclic olefins having two or more carbon atoms or/and
20 from cyclic olefins having four or more carbon atoms, in each case corresponding to the general formula **VII**, by olefin metathesis reaction in the presence of at least one catalyst, wherein
a catalyst as claimed in any one of claims 1 to 7 is used
25 and R'^1 , R'^2 , R'^3 and R'^4 in the general formula **VII** represent hydrogen or/and hydrocarbon groups,
wherein the hydrocarbon group consists of identical or different straight-chain, branched, cyclic or/and non-cyclic radicals from the group alkyl radicals having from 1
30 to 50 carbon atoms, alkenyl radicals having from 1 to 50

carbon atoms, alkynyl radicals having from 1 to 50 carbon atoms, aryl radicals having from 1 to 30 carbon atoms, metallocenyl or/and silyl radicals, in which at least one hydrogen may optionally be replaced by a functional group, wherein R^{'1}, R^{'2}, R^{'3} and R^{'4} optionally represent one or more identical or different groups halogen, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio, sulfonyl or/and metallocenyl.

9. The process as claimed in claim 8, wherein the olefins that are used or/and that are to be prepared contain one or/and more than one double bond.

10. The process as claimed in claim 8 or 9, wherein one or more of R^{'1}, R^{'2}, R^{'3} and R^{'4}, identical or different, in the olefins of the general formula **VII**, in pairs, form a ring.

11. The process as claimed in any one of claims 8 to 10, wherein the hydrogen in the hydrocarbon groups R^{'1}, R^{'2}, R^{'3} and R^{'4} in the olefins of the general formula **VII** has been replaced partially or wholly by one or more identical or different groups halogen, silyl, nitro, nitroso, hydroxy, alkoxy, aryloxy, amino, amido, carboxyl, carbonyl, thio, sulfonyl or/and metallocenyl.

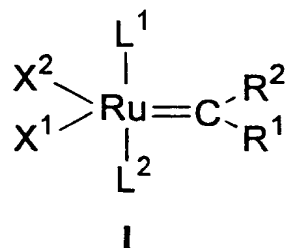
12. The process as claimed in any one of claims 8 to 11, wherein the process is carried out with or without a solvent, but preferably with organic solvents.

13. The process as claimed in any one of claims 8 to 12, wherein the process is carried out with the addition of a Brönstedt acid, preferably HCl, HBr, HI, HBF₄, HPF₆ or/and trifluoroacetic acid.

14. The process as claimed in any one of claims 8 to 12, wherein the process is carried out with the addition of a Lewis acid, preferably BF₃, AlCl₃ or/and ZnI₂.

Abstract:

The invention relates to a complex compound of ruthenium of the general structural formula I



- 5 in which X¹ and X² may be identical or different and represent an anionic ligand,
 in which R¹ and R² are identical or different, but may also have a ring,
 10 in which R¹ and R² represent hydrogen or/and a hydrocarbon group,
 in which the ligand L¹ is a N-heterocyclic carbene and in which the ligand L² is a neutral electron donor, especially a N-heterocyclic carbene or an amine, imine, phosphane,
 15 phosphite, stibine, arsine, carbonyl compound, carboxyl compound, nitrile, alcohol, ether, thiol or thioether, wherein R¹, R², R³ and R⁴ represent hydrogen or/and hydrocarbon groups.
- 20 The invention relates also to a process for the preparation of acyclic olefins having two or more carbon atoms or/and of cyclic olefins having four or more carbon atoms from acyclic olefins having two or more carbon atoms or/and from cyclic olefins having four or more carbon atoms by
 25 olefin metathesis reaction in the presence of at least one catalyst, wherein such a complex compound is used as catalyst and wherein R¹, R², R³ and R⁴ hydrogen or/and hydrocarbon groups.